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(54) **STEEL FIBRE FOR REINFORCING  
CONCRETE OR MORTAR HAVING AN  
ANCHORAGE END WITH AT LEAST THREE  
STRAIGHT SECTIONS**

USPC ..... 106/644; 428/593  
See application file for complete search history.

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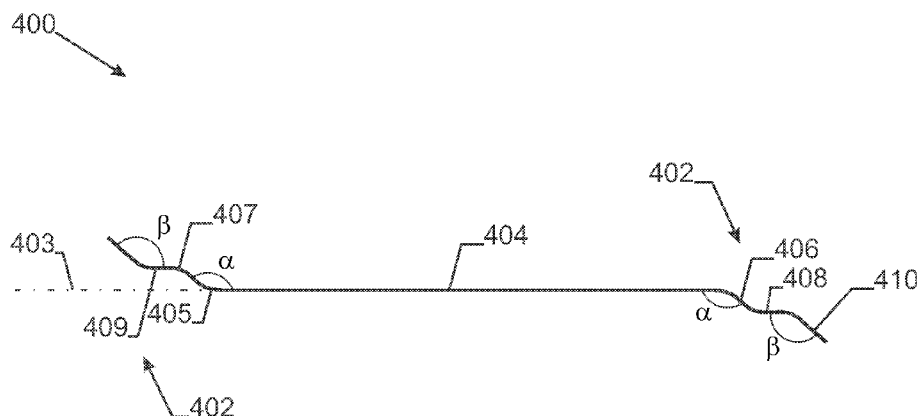
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(57) **ABSTRACT**

A steel fiber for reinforcing concrete or mortar has a middle  
portion and an anchorage end at one or both ends of the  
middle portion. The middle portion has a main axis. The  
anchorage end comprises at least a first straight section, a  
first bent section, a second straight section, a second bent  
section and a third straight section. The first straight section  
and the third straight section are bending away from the  
main axis of the middle portion in the same direction. The  
second straight section is substantially parallel with the main  
axis of said middle portion.

**17 Claims, 7 Drawing Sheets**



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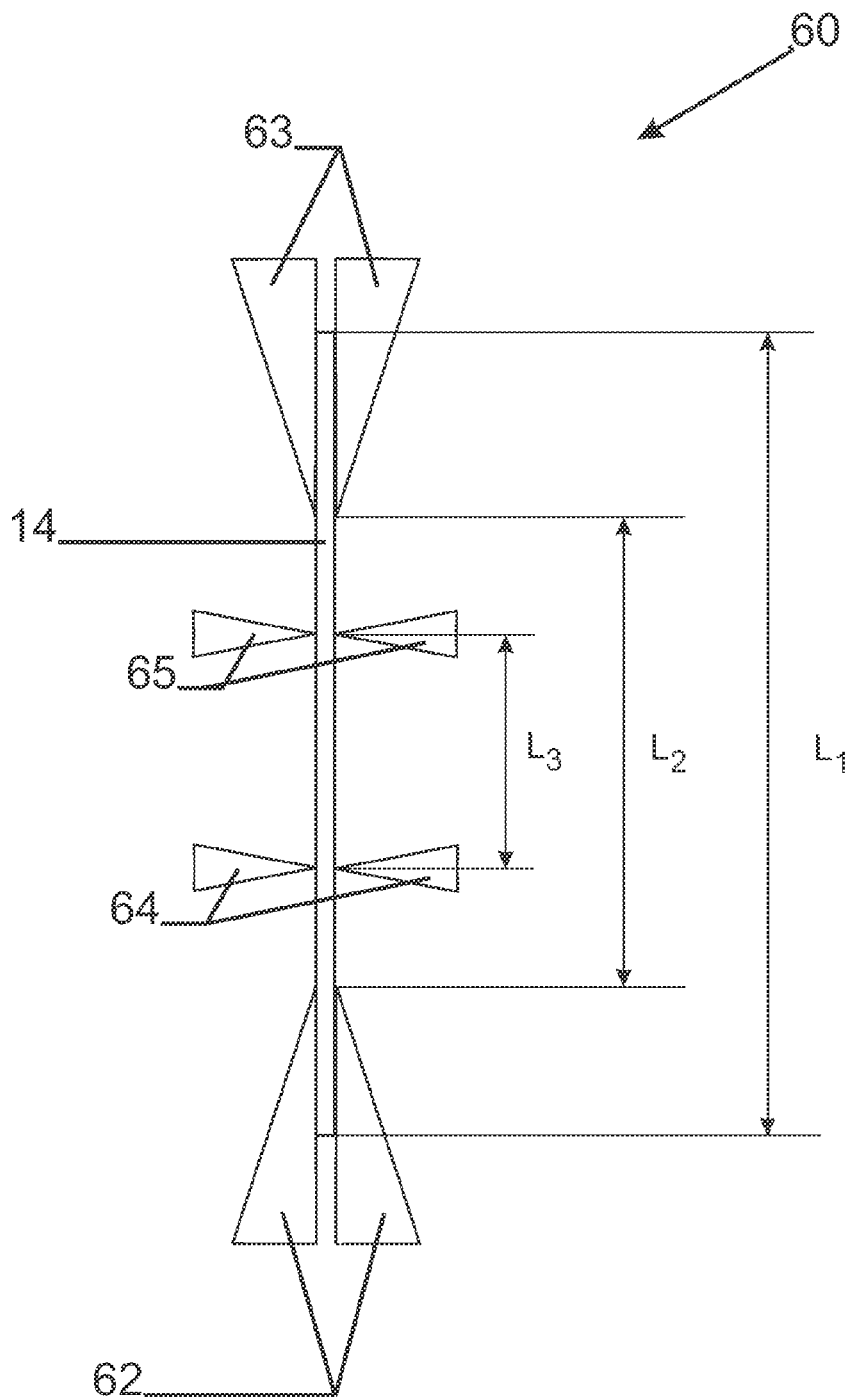


Fig. 1

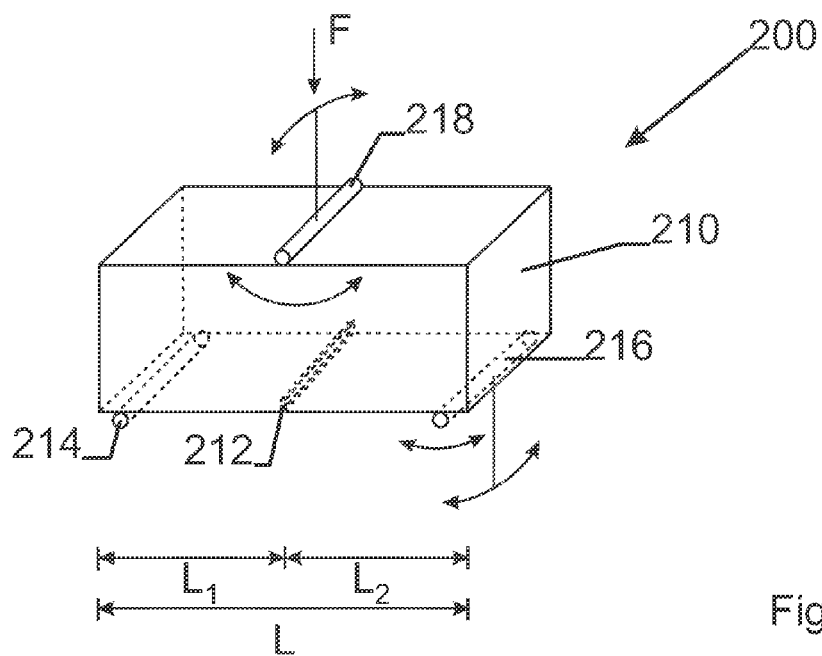


Fig. 2

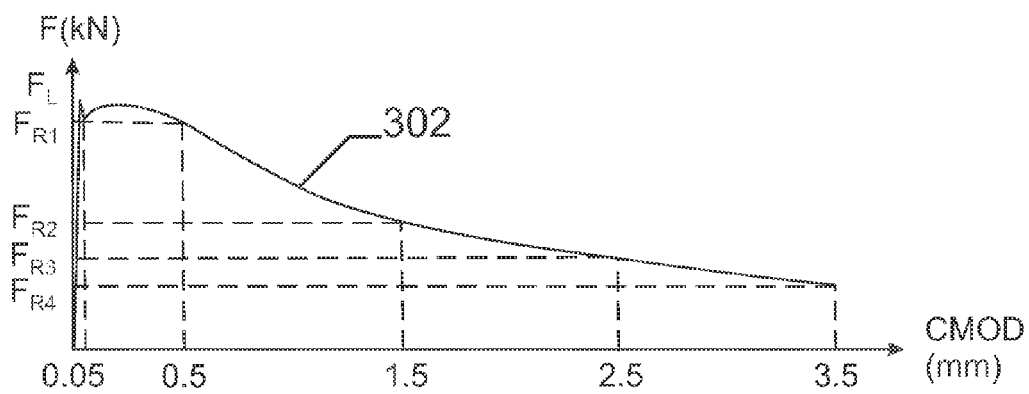


Fig. 3

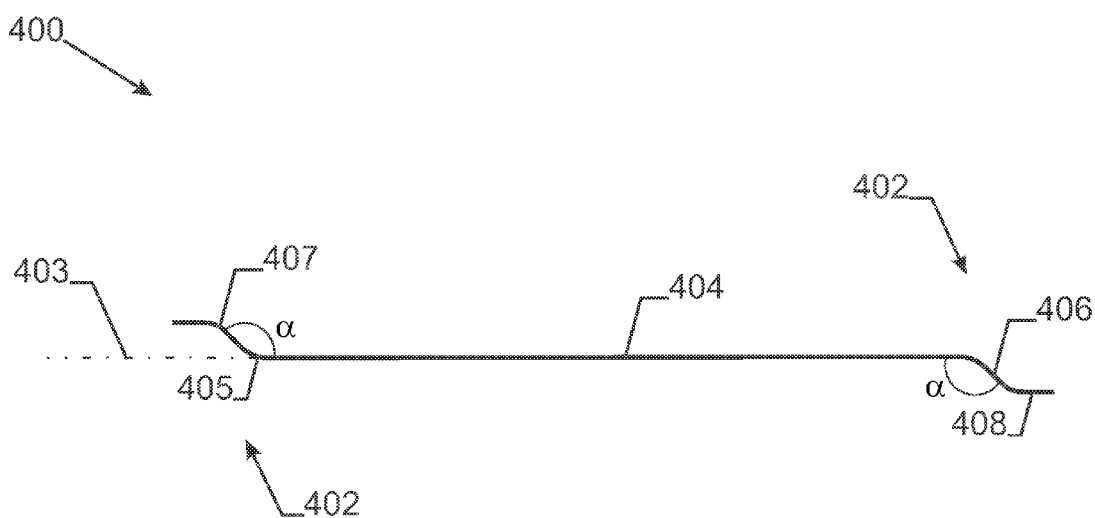


Fig. 4a

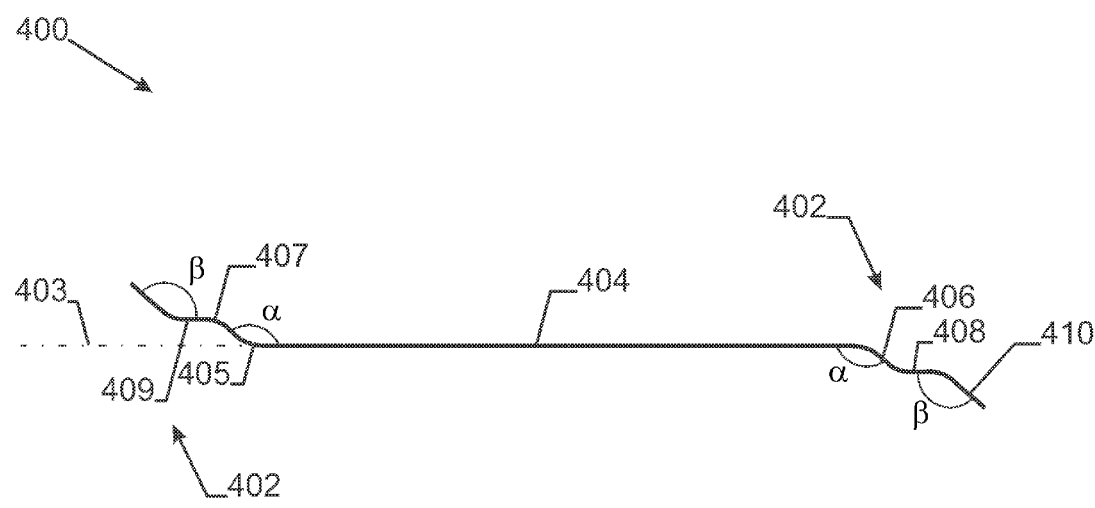


Fig. 4b

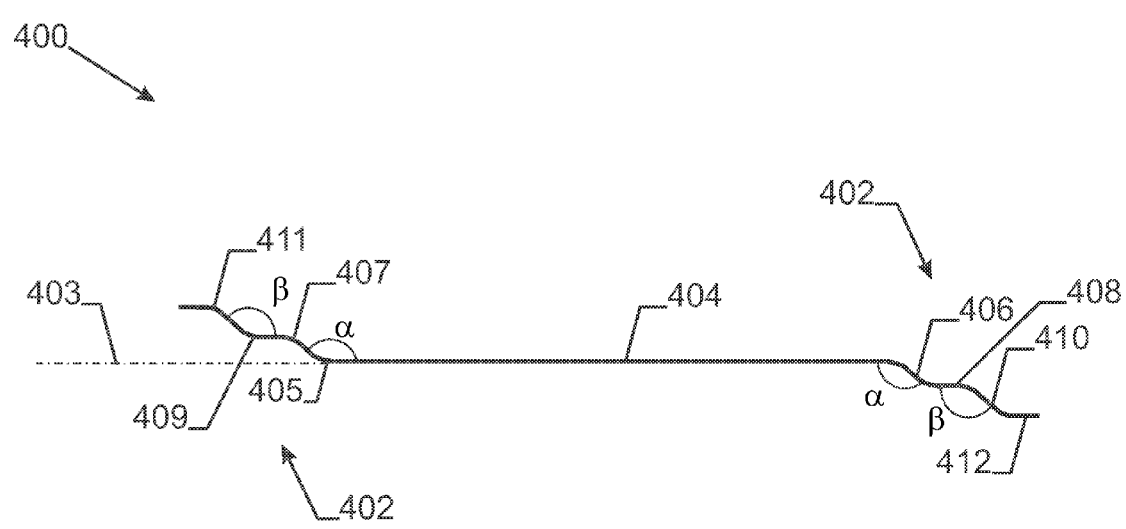


Fig. 4c

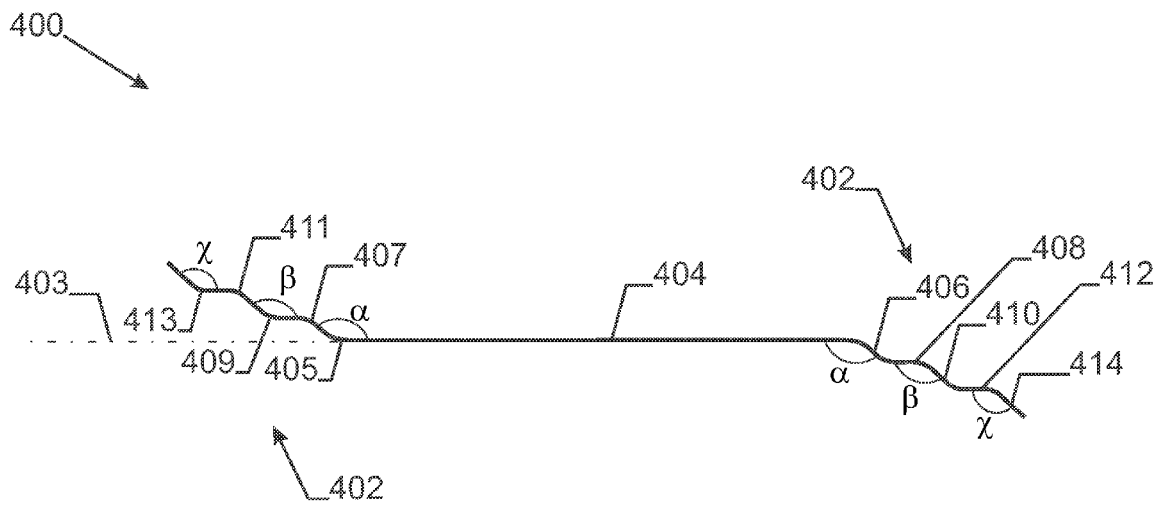


Fig. 4d



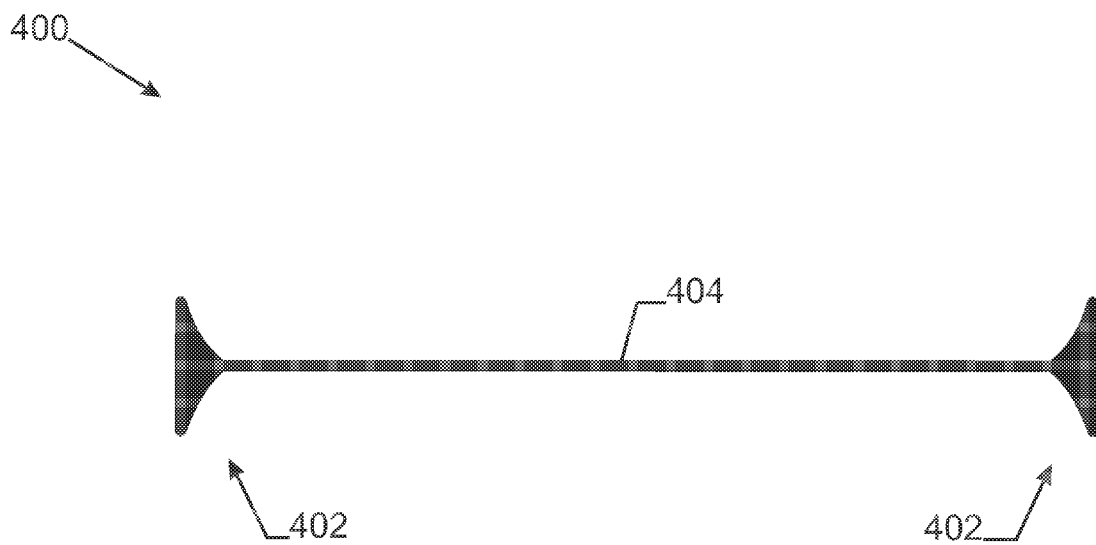


Fig. 4e

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# STEEL FIBRE FOR REINFORCING CONCRETE OR MORTAR HAVING AN ANCHORAGE END WITH AT LEAST THREE STRAIGHT SECTIONS

## TECHNICAL FIELD

The invention relates to steel fibres for reinforcing concrete or mortar provided with anchorage ends allowing to obtain a good anchorage when embedded in concrete or mortar. The steel fibres according to the present invention have at least one anchorage end with at least 3 straight sections. The steel fibres according to the present invention show a good performance at service-ability limit state (SLS) and at ultimate limit state (ULS) when embedded in concrete or mortar. The invention further relates to concrete or mortar structures comprising such steel fibres.

## BACKGROUND ART

Concrete is a brittle material having low tensile strength and low strain capacity. To improve properties of concrete like tensile strength and strain capacity, fibre reinforced concrete and more particularly metallic fibre reinforced concrete has been developed.

It is known in the art that the properties of the fibres like fibre concentration, fibre geometry and fibre aspect ratio greatly influences the performance of the reinforced concrete.

With respect to fibre geometry it is known that fibres having a shape different from a straight shape provide better anchorage of the fibre in the concrete or mortar.

It is furthermore known that fibres not showing the tendency to form balls when added to or mixed with concrete or mortar are preferred. Numerous examples of different fibre geometries are known in the art. There are for example fibres that are provided with undulations, either over the whole length or over part of their length. Examples of steel fibres undulated over their whole length are described in WO84/02732. Also fibres having hook-shaped ends are known in the art. Such fibres are for example described in U.S. Pat. No. 3,942,955.

Similarly, there are fibres of which the cross-section profile changes over the length, such as fibres provided with thickened and/or with flattened sections.

An example of a steel fibre provided with thickened sections is a steel fibre with thickenings in the form of a nail head at each of the extremities as described in U.S. Pat. No. 4,883,713.

Japanese patent 6-294017 describes the flattening of a steel fibre over its entire length. German Utility Model G9207598 describes the flattening of only the middle portion of a steel fibre with hook-shaped ends. U.S. Pat. No. 4,233,364 describes straight steel fibres provided with ends that are flattened and are provided with a flange in a plane essentially perpendicular to the flattened ends.

Steel fibres with flattened hook shaped ends are known from EP 851957 and EP 1282751.

Currently known prior art fibres for concrete reinforcement function very well in the known application fields like industrial flooring, sprayed concrete, pavement, . . .

However, the disadvantage of currently known prior art fibres is the relatively low performance at ultimate limit state (ULS) when low or moderate dosages of fibres are used. For more demanding structural applications, like beams and elevated slabs high dosages, typically from 0.5 vol % (40 kg/m<sup>3</sup>) onwards and not exceptionally up to 1.5 vol % (120

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kg/m<sup>3</sup>) are used to provide the necessary performance at ULS. These high dosages do not facilitate the mixing and placing of the steel fibre reinforced concrete.

Some prior art fibres do not perform at ULS as they break at crack mouth opening displacements (CMODs) lower than what is required for ULS. Other fibres, like fibres with hook shaped ends do not perform well at ULS as they are designed to be pulled out.

## DISCLOSURE OF INVENTION

It is an object of the present invention to provide steel fibres for the reinforcement of concrete or mortar avoiding the drawbacks of the prior art.

It is another object to provide steel fibres which are capable of bridging the crack mouth opening displacements greater than 0.5 mm, 1 mm, 1.5 mm, 2 mm, 2.5 mm or even greater than 3 mm during the three point bending test according to the European Standard EN 14651 (June 2005).

It is a further object of the present invention to provide steel fibres showing good anchorage in concrete or mortar.

It is a further object to provide steel fibres not showing the tendency to form balls when mixed in the concrete or mortar.

Furthermore it is an object of the present invention to provide steel fibres which may advantageously be used for structural applications whereby the steel fibres are used in low or moderate dosages, typically 1 vol % of steel fibres or 0.5 vol % of steel fibres.

Additionally it is another object to provide steel fibres that allow to reduce or to avoid the creep behaviour of cracked concrete reinforced with those fibres in the tension zone.

According to a first aspect of the present invention, there is provided a steel fibre for reinforcing concrete or mortar.

The steel fibre comprises a middle portion and an anchorage end at one or both ends of the middle portion. The middle portion has a main axis. The anchorage end or anchorage ends comprise(s) at least a first, a second and a third straight section. Each of the straight sections has a main axis, respectively the main axis of the first straight section, the main axis of the second straight section and the main axis of the third straight section.

The first straight section is connected to the middle portion by a first bent section; the second straight section is connected to the first straight section by a second bent section; the third straight section is connected to the second straight section by a third bent section.

This means that the first straight section is bent away from the middle portion by the first bent section; the second straight section is bent away from the first straight section by the second bent section and the third straight section is bent away from the second straight section by the third bent section.

The first straight section is bending away from the main axis of the middle portion thereby defining an included angle between the main axis of the middle portion and the main axis of the first straight section.

The second straight section is substantially parallel with the main axis of the middle portion.

The third straight section is bending away from the main axis of the middle portion in the same direction as the first straight section is bending away from the main axis of the middle portion thereby defining an included angle between the main axis of the second straight section and the main axis of said third straight section.

The included angle between the main axis of the middle portion and the main axis of said first straight section ranges preferably between 100 and 160 degrees. The included angle

between the main axis of the second straight section and the main axis of the third straight section ranges preferably between 100 and 160 degrees.

As mentioned above, the second straight section is substantially parallel with the main axis of the middle portion. With "substantially parallel" is meant that there can be some deviation from a parallel position. However, if there is deviation, this deviation is either small or accidental. With a small deviation is meant that the deviation from a parallel position is less than 15 degrees, more preferably less than 10 degrees.

Two straight sections with a common vertex define two angles. The sum of these two angle is equal to 360 degrees. For the purpose of this invention the smallest of the two angles defined by two straight sections with a common vertex is called the "included angle".

This means that the included angle between the main axis of the middle portion and the main axis of the first straight section is the smallest angle defined by the main axis of the middle portion and the main axis of the first straight section. Similarly, the included angle between the main axis of the second straight section and the main axis of the third straight section is the smallest angle defined by the main axis of the second straight section and the main axis of the third straight section.

As mentioned above the included angle between the main axis of the middle portion and the main axis of the first straight section preferably ranges between 100 and 160 degrees. This means that the angle supplementary to the included angle between the main axis of the middle portion and the main axis of the first straight section ranges between 20 and 80 degrees.

If the included angle between the main axis of the middle portion and the main axis of the first straight section is higher than 160 degrees (or the supplementary angle of this included angle is lower than 20 degrees), the anchorage in concrete or mortar is limited and also the performance in SLS and ULS is poor. Such a fibre shows the tendency to be pulled out. If the included angle between the main axis of the middle portion and the main axis of the first straight section is lower than 100 degrees (or the supplementary angle of this included angle is higher than 80 degrees), the fibres are coagulating and do not mix homogeneously in the concrete or mortar.

More preferably, the included angle between the main axis of the middle portion and the main axis of the first straight section is ranging between 110 and 160 (consequently the supplementary angle is ranging between 20 and 70 degrees), for example between 120 and 160 degrees (consequently the supplementary angle is ranging between 20 and 60 degrees), for example 150 degrees (consequently the supplementary angle is 30 degrees) or 140 degrees (consequently the supplementary angle is 40 degrees).

Similarly, the included angle between the main axis of the second straight section and the main axis of the third straight section ranges preferably between 100 and 160 degrees. This means that the angle supplementary to the included angle between the second straight section and the main axis of the third straight section ranges between 20 and 80 degrees. If the included angle between the main axis of the second straight section and the main axis of the third straight section is higher than 160 degrees (or the supplementary angle of this included angle is lower than 20 degrees), the anchorage in concrete or mortar is limited and also the performance in SLS and ULS is poor. Such a fibre shows the tendency to be pulled out.

If the included angle between the main axis of the second straight section and the main axis of the third straight section is lower than 100 degrees (or the supplementary angle of this included angle is higher than 80 degrees), the fibres are coagulating and do not mix homogeneously in the concrete or mortar.

More preferably, the included angle between the main axis of the second straight section and the main axis of the third straight section is ranging between 110 and 160 (consequently the supplementary angle is ranging between 20 and 70 degrees), for example between 120 and 160 degrees (consequently the supplementary angle is ranging between 20 and 60 degrees), for example 150 degrees (consequently the supplementary angle is 30 degrees) or 140 degrees (consequently the supplementary angle is 40 degrees).

The included angle between the main axis of the middle portion and the main axis of the first straight section and the included angle between the main axis of the second straight section and the main axis of the third straight section can be equal or can be different.

In a particular embodiment the included angle between the main axis of the middle portion and the main axis of the first straight section and the included angle between the main axis of the second straight section and the main axis of the third straight section are the same or substantially the same. In this particular embodiment the main axis of the first straight section and the main axis of the third straight section are parallel or substantially parallel.

In preferred embodiments of the present invention the anchorage end further comprises a fourth straight section. This fourth straight section is connected to the third straight section by a fourth bent section. This means that the fourth straight section is bending away from the third straight section by the fourth bent section.

Preferably, but not necessarily, the fourth straight section is parallel with the main axis of the middle portion and with the main axis of the second straight section.

A steel fibre having four straight sections whereby the second and the fourth straight section are parallel with the main axis of the middle portion shows a very good performance in SLS and ULS when embedded in concrete or mortar.

In an alternative embodiment the second straight section has a main axis that is substantially parallel with the main axis of the middle portion of the steel fibre and the fourth straight section is not parallel with the main axis of the middle portion of the steel fibre. In this case the angle between the fourth straight section and the main axis of the middle portion ranges between -60 and +60 degrees, for example between -45 and +45 degrees or between -30 and +30 degrees.

The anchorage end of a steel fibre according to the present invention has at least three straight sections.

In principle there is no limitation to the number of straight sections of an anchorage ends. However, the most preferred embodiments have anchorage ends with three straight sections, four straight sections, five straight sections or six straight sections. In each of these embodiments there is a bent section between each two consecutive straight sections. Surprisingly, it has been found that an anchorage end having three straight sections and four straight sections shows the best performance when embedded in concrete or mortar both in a pull out test and in a three point bending test.

The straight sections, for example the first, second, third and/or fourth straight section, preferably have a length ranging between 0.1 mm and 8 mm, more preferably between 0.1 mm and 5 mm, for example 0.5 mm or 2 mm.

The lengths of the different straight sections can be chosen independently from each other. This means that the different straight sections can have the same length or different lengths.

In preferred embodiments the length of the different straight sections is equal.

An example comprises a steel fibre having a first, second, third and fourth straight section, all straight sections having a length of 2 mm.

An alternative example comprises a steel fibre having a first straight section having a length of 0.5 mm, a second straight section having a length of 2 mm, a third straight section having a length of 0.5 mm and a fourth straight section having a length of 2 mm.

The first bent section has a first radius of curvature, the second bent section has a second radius of curvature, the third bent section has a third radius of curvature, the fourth bent section (if present) has a fourth radius of curvature.

The radius of curvature of the bent sections is preferably ranging between 0.1 mm and 5 mm, for example between 0.5 mm and 3 mm, for example 1 mm, 1.2 mm or 2 mm.

The radius of curvature of the different bent sections of the steel fibre can be chosen independently from each other. This means that the radius of the first bent section, of the second bent section, of the third bent sections and of the fourth bent section (if present) can be the same or can be different.

A steel fibre according to the present invention may be provided with one anchorage end at one end of the middle portion. Preferably, a steel fibre is provided with an anchorage end at both ends of the steel fibre. In case the steel fibre is provided with an anchorage end at both ends of the middle portion the two anchorage ends can be the same or can be different.

For a steel fibre having an anchorage end at both ends of the middle portion, both anchorage ends may be bending away (deflecting) in the same direction from the main axis of the middle portion of the steel fibre (symmetric fibres).

Alternatively, one anchorage end may be bending away (deflecting) in one direction from the main axis of the middle portion of the steel fibre while the other anchorage end is bending away (deflecting) in the opposite direction from the main axis of the middle portion of the steel fibre (asymmetric fibres).

For a steel fibre according to the present invention, the middle portion and the anchorage end is preferably situated in one plane or are substantially situated in one plane.

The other anchorage end, if any, may be situated in the same plane or in another plane.

An advantage of steel fibres according to the present invention is that they do not coagulate when being mixed with concrete or mortar. This results in a homogeneous distribution of the steel fibres over the concrete or mortar.

The steel fibres according to the present invention perform particularly well both at service-ability limit state (SLS) of a concrete or mortar structure and at ultimate limit state (ULS) when used at moderate or low dosage, i.e. at a dosage of less than 1 vol % or less than 0.5 vol %, for example 0.25 vol %.

It is known in the art that increasing the amount of fibres in concrete positively influences the performance of fibre reinforced concrete. A big advantage of the present invention is that good performance at SLS and ULS is obtained with moderate or low dosage of steel fibres.

For this invention the material properties used for evaluating the performance in ULS and SLS of steel fibre reinforced concrete is the residual flexural tensile strength  $f_{R,t}$ .

The residual flexural tensile strength is derived from the load at a predetermined crack mouth opening displacement (CMOD) or midspan deflection ( $\delta_R$ ).

The residual flexural tensile strengths are determined by means of a three point bending test according to European Standard EN 14651 (described further in this application).

The residual flexural tensile strength  $f_{R,1}$  is determined at  $CMOD_1=0.5$  mm ( $\delta_{R,1}=0.46$  mm), the residual flexural tensile strength  $f_{R,2}$  is determined at  $CMOD_2=1.5$  mm ( $\delta_{R,2}=1.32$  mm), the residual flexural tensile strength  $f_{R,3}$  is determined at  $CMOD_3=2.5$  mm ( $\delta_{R,3}=2.17$  mm) and the residual flexural tensile strength  $f_{R,4}$  is determined at  $CMOD_4=3.5$  mm ( $\delta_{R,4}=3.02$  mm).

The residual flexural tensile strength  $f_{R,1}$  is the key requirement for SLS design.

The residual flexural tensile strength  $f_{R,3}$  is the key requirement for ULS design.

For steel fibres according to the present invention—contrary to the steel fibres known in the art—the ratio residual flexural strength  $f_{R,3}$  divided by residual flexural strength  $f_{R,1}$  ( $f_{R,3}/f_{R,1}$ ) is high even when low or moderate dosages of steel fibres are used as for example dosages lower than 1 vol % or dosages lower 0.5 vol %, for example 0.25 vol %.

For fibres according to the present invention the ratio  $f_{R,3}/f_{R,1}$  is preferably higher than 1 and more preferably higher than 1.05 or higher than 1.15 for example 1.2 or 1.3 when dosages lower than 1 vol % or dosages lower than 0.5 vol %, for example 0.25 vol % are used.

For concrete reinforced with steel fibres according to the present invention with a dosage of 0.5 vol %, the residual flexural tensile strength  $f_{R,3}$  using a C35/45 concrete is higher than 3.5 MPa, preferably higher than 5 MPa, more preferably higher than 6 MPa as for example 7 MPa.

Fibres known in the art as for example steel fibres having conically shaped ends (nail heads) made of low carbon steel function well for limiting the width or growth of up to about 0.5 mm (SLS). However, these fibres have a low performance at ULS. This type of steel fibres breaks at crack mouth opening displacements lower than required for ULS.

The ratio  $f_{R,3}/f_{R,1}$  is lower than 1 for moderate dosages in a normal strength concrete, for example C35/45 concrete.

Other fibres known in the art are fibres with hook shaped ends as for example known from EP 851957 are designed to pull out.

Also for this type of fibres the ratio  $f_{R,3}/f_{R,1}$  is lower than 1 for moderate dosages in a normal strength concrete.

Maximum Load Capacity  $F_m$ —Tensile Strength  $R_m$

A steel fibre according to the present invention, i.e. the middle portion of a steel fibre according to the present invention preferably has a high maximum load capacity  $F_m$ . The maximum load capacity  $F_m$  is the greatest load that the steel fibre withstands during a tensile test. The maximum load capacity  $F_m$  of the middle portion is directly related to the tensile strength  $R_m$  of the middle portion as the tensile strength  $R_m$  is the maximum load capacity  $F_m$  divided by the original cross-section area of the steel fibre.

For a steel fibre according to the present invention, the tensile strength of the middle portion of the steel fibre is preferably above 1000 MPa and more particularly above 1400 MPa, e.g. above 1500 MPa, e.g. above 1750 MPa, e.g. above 2000 MPa, e.g. above 2500 MPa.

The high tensile strength of steel fibres according to the present invention allows the steel fibres to withstand high loads.

A higher tensile strength is thus directly reflected in a lower dosage of the fibres. However using steel fibres having

a high tensile strength is only meaningful if the steel fibres show a good anchorage in the concrete.

#### Elongation at Maximum Load

According to a preferred embodiment the steel fibre according to the present invention, more particularly the middle portion of a steel fibre according to the present invention has an elongation at maximum load  $A_{g+e}$  of at least 2.5%.

According to particular embodiments of the present invention, the middle portion of the steel fibre has an elongation at maximum load  $A_{g+e}$  higher than 2.75%, higher than 3.0%, higher than 3.25%, higher than 3.5%, higher than 3.75%, higher than 4.0%, higher than 4.25%, higher than 4.5%, higher than 4.75%, higher than 5.0%, higher than 5.25%, higher than 5.5%, higher than 5.75% or even higher than 6.0%.

Within the context of the present invention, the elongation at maximum load  $A_{g+e}$  and not the elongation at fraction  $A_t$  is used to characterise the elongation of a steel fibre, more particularly of the middle portion of a steel fibre.

The reason is that once the maximum load has been reached, constriction of the available surface of the steel fibre starts and higher loads are not taken up.

The elongation at maximum load  $A_{g+e}$  is the sum of the plastic elongation at maximum load  $A_g$  and the elastic elongation.

The elongation at maximum load does not comprise the structural elongation  $A_s$  which may be due to the wavy character of the middle portion of the steel fibre (if any). In case of a wavy steel fibre, the steel fibre is first straightened before the  $A_{g+e}$  is measured.

The high degree of elongation at maximum load  $A_{g+e}$  may be obtained by applying a particular stress-relieving treatment such as a thermal treatment to the steel wires where the steel fibres will be made of. In this case at least the middle portion of the steel fibre is in a stress-relieved state.

Steel fibres having a high ductility or a high elongation at maximum load are preferred, these fibres will not break at CMOD's above 0.5 mm, above 1.5 mm, above 2.5 mm or above 3.5 mm in the three point bending test according to EN 14651.

#### Anchorage Force

Preferably, the steel fibre according to the present invention has a high degree of anchorage in concrete or mortar.

By providing the middle portion of the steel fibre with anchorage ends according to the present invention the anchorage of the steel fibre in concrete or mortar is considerably improved.

A high degree of anchorage will avoid pull-out of the fibres.

A high degree of anchorage combined with a high elongation at maximum strength will avoid pull-out of the fibres, will avoid fibre failure and will avoid brittle failure of concrete in tension.

A high degree of anchorage combined with a high tensile strength allows that better use is made of the tensile strength after the occurrence of cracks.

Steel fibres according to the present invention have for example a tensile strength  $R_m$  higher than 1000 MPa and an elongation at maximum load  $A_{g+e}$  of at least 1.5%, a tensile strength  $R_m$  of at least 1000 MPa and an elongation at maximum load  $A_{g+e}$  of at least 2.5%, a tensile strength  $R_m$  of at least 1000 MPa and an elongation at maximum load  $A_{g+e}$  of at least 4%.

In a preferred embodiment the steel fibres have a tensile strength  $R_m$  of at least 1500 MPa and an elongation at maximum load  $A_{g+e}$  of at least 1.5%, a tensile strength  $R_m$

of at least 1500 MPa and an elongation at maximum load  $A_{g+e}$  of at least 2.5%, a tensile strength  $R_m$  of at least 1500 MPa and an elongation at maximum load  $A_{g+e}$  of at least 4%.

In further preferred embodiments the steel fibres have a tensile strength  $R_m$  of at least 2000 MPa and an elongation at maximum load  $A_{g+e}$  of at least 1.5%, a tensile strength  $R_m$  of at least 2000 MPa and an elongation at maximum load  $A_{g+e}$  of at least 2.5%, a tensile strength  $R_m$  of at least 2000 MPa and an elongation at maximum load  $A_{g+e}$  of at least 4%.

Fibres having a high tensile strength  $R_m$  may withstand high loads. Fibres characterised by a high elongation at maximum load  $A_{g+e}$  will not break at CMODs above 0.5 mm, above 1.5 mm, above 2.5 mm or above 3 mm in the three point bending test according to EN 14651.

The middle portion of the steel fibre can be straight or rectilinear; or can be wavy or undulated. Preferably, the middle portion of the steel fibres is straight or rectilinear. In case the middle portion is wavy or undulated the main axis of the middle portion is defined as the line crossing the wavy or undulated middle portion in such a way that the total area of the upper waves or undulations above this line is the same as the total area of the waves or undulations under this line.

The steel fibres, more particularly the middle portion may have any cross-section such as a circular cross-section, a substantially circular cross-section, a rectangular cross-section, a substantially rectangular cross-section, an oval cross-section, a substantially oval cross-section, . . .

The steel fibres, more particularly the middle portion of the steel fibres typically have a diameter  $D$  ranging between 0.10 mm to 1.20 mm, for example ranging between 0.5 mm and 1 mm, more particularly 0.7 mm or 0.9 mm. In case the cross-section of the steel fibre and more particularly of the middle portion of the steel fibre is not round, the diameter is equal to the diameter of a circle with the same surface area as the cross-section of the middle portion of the steel fibre.

The steel fibres typically have a length to diameter ratio  $L/D$  ranging from 40 to 100.

The length of the steel fibres is for example 50 mm, 55 mm, 60 mm or 65 mm.

With length of a steel fibre is meant the total length of the steel fibre i.e. the sum of the length of middle portion and the length of the anchorage end or anchorage ends.

The middle portion has preferably a length higher than 25 mm, for example higher than 30 mm, higher than 40 mm or higher than 45 mm.

The steel fibre or part of the steel fibre can be flattened or can be provided with one or more flattened sections. For example the middle portion, part of the middle portion, an anchorage end or part of an anchorage end can be flattened or can be provided with one or more flattened sections. Also combinations can be considered.

If the middle portion is provided with one or more flattened sections, the flattened section or sections is preferably located close to but not immediately adjacent to the anchorage end or anchorage ends.

According to a second aspect a reinforced concrete structure comprising a concrete structure reinforced with steel fibres according to the present invention is provided. The reinforced concrete structure may or may not be reinforced with traditional reinforcement (for example pre-stressed or post-tensioned reinforcement) in addition to the steel fibres according to the present invention.

For a reinforced concrete structure reinforced with steel fibres according to the present invention the ratio residual flexural tensile strength  $f_{R,3}$ /residual flexural tensile strength  $f_{R,1}$  ( $f_{R,3}/f_{R,1}$ ) is preferably higher than 1 and more preferably higher than 1.05, higher than 1.15 or higher than 1.2, for

example 1.3. This ratio is reached when low dosages of steel fibres are used, for example a dosage lower than 1 vol % or a dosage lower than 0.5 vol %, or even with a dosage of 0.25 vol %.

The residual flexural tensile strength  $f_{R,3}$  of a reinforced concrete structure using steel fibres according to the present invention is preferably higher than 3.5 MPa, more preferably the residual flexural tensile strength  $f_{R,3}$  is higher than 4.5 MPa, higher than 5 MPa or even higher than 6 MPa.

The concrete structure reinforced with fibres according to the present invention has an average post crack residual strength at ULS exceeding 3 MPa, e.g. more than 4 MPa, e.g. more than 5 MPa, 6 MPa, 7 MPa, 7.5 MPa. By using steel fibres according to the present invention, concrete structures having an average post crack residual strength at ULS exceeding 3 MPa or exceeding 4 MPa can be reached using C35/45 concrete and using dosages of less than 1 vol % or even less than 0.5 vol %.

According to the present invention preferred reinforced concrete structures have an average post crack residual strength at ULS exceeding 5 MPa using C35/45 concrete and using dosages of less than 1 vol % or even less than 0.5 vol %.

It is important to notice that reinforced concrete structures having an average post crack residual strength at ULS exceeding 3 MPa or 5 MPa are existing. However, these reinforced concrete structure known in the art use high dosages of steel fibres (above 0.5 vol % or above 1 vol %) in normal strength concrete or high strength concrete or use moderate dosages of high strength fibres in high strength concrete.

According to a third aspect the use of steel fibres according to the present invention for load carrying structures of concrete is provided.

#### BRIEF DESCRIPTION OF FIGURES IN THE DRAWINGS

The invention will now be described into more detail with reference to the accompanying drawings where

FIG. 1 illustrates a tensile test (load-strain test) of a steel fibre;

FIG. 2 illustrates a three point bending test (load-crack mouth opening displacement curve or a load-deflection curve);

FIG. 3 illustrates a load-crack mouth opening displacement curve;

FIG. 4a, FIG. 4b, FIG. 4c, FIG. 4d and FIG. 4e illustrate a number of different embodiments of prior art steel fibres and steel fibres provided with anchorage ends according to the present invention.

#### MODE(S) FOR CARRYING OUT THE INVENTION

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. The dimensions and the relative

The following terms are provided solely to aid in the understanding of the inventions.

Maximum load capacity ( $F_m$ ): the greatest load which the steel fibre withstands during a tensile test;

Elongation a maximum load (%): increase in the gauge length of the steel fibre at maximum force, expressed as a percentage of the original gauge length;

Elongation at fracture (%): increase in the gauge length at the moment of fracture expressed as a percentage of the original gauge length;

Tensile strength ( $R_m$ ): stress corresponding to the maximum load ( $F_m$ );

Stress: force divided by the original cross-sectional area of the steel fibre;

Dosage: quantity of fibres added to a volume of concrete (expressed in  $\text{kg/m}^3$  or in vol % (1 vol % corresponds with  $78.50 \text{ kg/m}^3$ ; 0.5 vol % corresponds with  $40 \text{ kg/m}^3$ ));

Normal strength concrete : concrete having a strength less than or equal to the strength of concrete of the C50/60 strength classes as defined in EN206;

High strength concrete : concrete having a strength higher than the strength of concrete of the C50/60 strength classes as defined in EN 206.

To illustrate the invention a number of different steel fibres, both prior art steel fibres and steel fibres according to the present invention are subjected to two different tests :

a tensile test (load-strain test); and

a three point bending test (load-crack mouth opening displacement curve or a load-deflection curve).

The tensile test is applied on the steel fibre, more particularly on the middle portion of the steel fibre. Alternatively, the tensile test is applied on the wire used to make the steel fibre.

The tensile test is used to determine the maximum load capacity  $F_m$  of the steel fibre and to determine the elongation at maximum load  $A_{g+e}$ .

The three point bending test is applied on a notched reinforced beam as specified in EN 14651.

The test is used to determine the residual tensile strengths.

The tests are illustrated in FIG. 1 and FIG. 2 respectively.

FIG. 1 shows a test set up 60 of a tensile test (load-strain test) of a steel fibre). With the help of the test set up 60 steel fibres are tested as to maximum load capacity  $F_m$  (breaking load), tensile strength  $R_m$  and total elongation at maximum load  $A_{g+e}$ .

The anchorage ends (for example the enlarged or hook shaped ends) of the steel fibre to be tested are cut first. The remaining middle portion 14 of the steel fibre is fixed between two pairs of clamps 62, 63. Through the clamps 62, 63 an increasing tensile force  $F$  is exercised on the middle portion 14 of the steel fibre. The displacement or elongation as a result of this increasing tensile force  $F$  is measured by measuring the displacement of the grips 64, 65 of the extensometer.  $L_1$  is the length of the middle portion of the steel fibre and is e.g. 50 mm, 60 mm or 70 mm.  $L_2$  is the distance between the clamps and is e.g. 20 mm or 25 mm.  $L_3$  is the extensometer gauge length and is minimum 10 mm, e.g. 12 mm, e.g. 15 mm. For an improved grip of the extensometer to the middle portion 14 of the steel fibre, the middle portion of the steel fibre can be coated or can be covered with a thin tape to avoid slippery of the extensometer over the steel fibre. By this test a load-elongation curve is recorded.

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The percentage total elongation at maximum load is calculated by the following formula:

$$A_{g+e} = \frac{\text{extension at maximum load}}{\text{extensometer gauge length } L_3} \times 100$$

With the help of setup **60** of FIG. **1**, a number of different wires are tested as to maximum load capacity  $F_m$  (breaking load), tensile strength  $R_m$  and total elongation at maximum load  $A_{g+e}$ .

Five tests per specimen are done. Table 1 gives an overview of the wires that are tested.

TABLE 1

Wire type	Carbon content	Diameter (mm)	$F_m$ (N)	$R_m$ (MPa)	$A_{g+e}$ (%)
1	Low	1.0	911	1160	1.86
2	Low	0.9	751	1181	2.16
3	High	0.89	1442	2318	5.06
4	Medium	0.75	533	1206	2.20
5	Medium	0.90	944	1423	1.84

Low carbon steel is defined as steel having a carbon content of maximum 0.15%, for example 0.12%; medium carbon steel is defined as steel having a carbon content ranging between 0.15% and 0.44%, for example 0.18% and high carbon steel is defined as steel having a carbon content higher than 0.44%, for example 0.5% or 0.6%.

FIG. **2** shows the experimental set up **200** of a three point bending test. The three point bending test was performed at 28 days according to European Standard EN 14651 using a 150×150×600 mm prismatic specimen **210**. In the mid-span of the specimen **210** a single notch **212** with a depth of 25 mm was sawn with a diamond blade to localize the crack. The set up comprises two supporting rollers **214**, **216** and one loading roller **218**. The setup is capable of operating in a controlled manner, i.e. producing a constant rate of displacement (CMOD or deflection). The tests were carried out with a displacement rate as specified in EN 14651. A load-crack mouth opening displacement curve or a load-deflection curve is recorded.

An example of a load-crack mouth opening displacement curve **302** is given in FIG. **3**.

The residual flexural strength  $f_{R,i}$  ( $i=1,2,3$  or  $4$ ) are assessed according to EN 14651 and can be calculated by the following expression :

$$f_{R,i} = \frac{3F_{R,i}L}{2bh_{sp}^2} (\text{N/mm}^2)$$

with:

$F_{R,i}$ =the load corresponding with  $\text{CMOD}=\text{CMOD}_i$  or  $\delta=\delta_{R,i}$  ( $i=1,2,3,4$ );

$b$ =width of the specimen (mm);

$h_{sp}$ =distance between tip of the notch and the top of the specimen (mm);

$L$ =span length of the specimen (mm).

With the help of setup **200** of FIG. **2**, the performance of a number of different steel fibres (FIB1 till FIB5) in concrete is tested. For the test the steel fibres are embedded in C35/45 concrete. The curing time was 28 days.

An overview of the steel fibres that are tested is given in Table 2. The test results of the prior art steel fibres (FIB1 and FIB5) are given in Table 3.

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The test results of the steel fibres according to the present invention (FIB2, FIB3 and FIB4) are given in Table 4.

The steel fibres are specified by the length of the steel fibre, the wire type used to make the steel fibre, the diameter of the steel fibre (more particularly the diameter of the middle portion of the steel fibre), the number of straight sections of the anchorage end, the included angle between the main axis of the middle portion and the main axis of the first straight section, the orientation of the second straight section towards the middle portion, the included angle between the main axis of the second straight section and the main axis of the third straight section, the orientation of the fourth straight section towards the middle portion, the included angle between the main axis of the fourth straight section and the main axis of the fifth straight section.

The geometry of the different fibres is shown in FIG. **4a** to FIG. **4e**. All tested fibres **400** have anchorage ends **402** at both ends of the middle portions **404**.

Steel fibres FIB1 and FIB5 are prior art fibres. Steel fibre FIB1 is a low carbon fibre having anchorage ends with two straight sections. Steel fibre FIB5 is a fibre having at both ends a nail head as anchorage end.

Steel fibres FIB2, FIB3 and FIB4 are fibres according to the present invention. Steel fibres FIB2, FIB3 and FIB4 have anchorage ends with respectively 3 straight sections (FIG. **4b**), 4 straight sections (FIGS. **4c**) and 5 straight sections (FIG. **4d**).

The steel fibre **400** shown in FIG. **4a** comprises a middle portion **404** and an anchorage end **402** at both ends of the middle portion **404**. The middle portion **404** has a main axis **403**. Each of the anchorage ends **402** comprises a first bent section **405**, a first straight section **406**, a second bent section **407** and a second straight section **408**. The included angle between the main axis **403** of middle portion **404** and the main axis of the first straight section **406** is indicated by  $\alpha$ .

The second straight section **408** is parallel or substantially parallel with the main axis **403** of the middle portion **404**.

The steel fibre **400** shown in FIG. **4b** comprises a middle portion **404** and an anchorage end **402** at both ends of the middle portion **404**. The middle portion has a main axis **403**. Each of the anchorage ends **402** comprises a first bent section **405**, a first straight section **406**, a second bent section **407**, a second straight section **408**, a third bent section **409** and a third straight section **410**. The included angle between the main axis **403** of the middle portion **404** and the main axis of the first straight section **406** is indicated by  $\alpha$ . The included angle between the main axis of the second straight section **408** and the main axis of the third straight section **410** is indicated by  $\beta$ .

The second straight section **408** is parallel or substantially parallel with the main axis **403** of the middle portion **404**.

The steel fibre **400** shown in FIG. **4c** comprises a middle portion **404** and an anchorage end **402** at both ends of the middle portion **404**. The middle portion has a main axis **403**. Each of the anchorage ends **402** comprises a first bent section **405**, a first straight section **406**, a second bent section **407**, a second straight section **408**, a third bent section **409**, a third straight section **410**, a fourth bent section **411** and a fourth straight section **412**. The included angle between the main axis **403** of the middle portion **404** and the main axis of the first straight section **406** is indicated by  $\alpha$ . The included angle between the main axis of the second straight section **408** and the main axis of the third straight section **410** is indicated by  $\beta$ .

The second straight section **408** and the fourth straight section **412** are parallel or substantially parallel with the main axis **403** of the middle portion **404**.

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The steel fibre 400 shown in FIG. 4d comprises a middle portion 404 and an anchorage end 402 at both ends of the middle portion 404. The middle portion has a main axis 403. Each of the anchorage ends 402 comprises a first bent section 405, a first straight section 406, a second bent section 407, a second straight section 408, a third bent section 409, a third straight section 410, a fourth bent section 411, a fourth straight section 412, a fifth bent section 413 and a fifth straight section 414. The included angle between the main axis 403 of the middle portion 404 and the main axis of the first straight section 406 is indicated by  $\alpha$ . The included angle between the main axis of the second straight section 408 and the main axis of the third straight section 410 is indicated by  $\beta$ . The included angle between the main axis of the fourth straight section 412 and the main axis of the fifth straight section 414 indicated by  $\gamma$ . The second straight section 408 and the fourth straight section 412 are parallel or substantially parallel with the main axis 403 of the middle portion 404.

The fibre shown in FIG. 4e comprises a middle portion 404 provided at both ends of the middle portion 404 with anchorage ends 402. The anchorage ends 402 comprise nail heads.

TABLE 2

Fibre type	Length (mm)	Wire type	Diameter (mm)	Number of straight sections	$\alpha$ (degrees)	2 <sup>nd</sup> straight section parallel with main axis middle portion (yes/no)	$\beta$ (degrees)	4 <sup>th</sup> straight section parallel with main axis middle portion (yes/no)	$\gamma$ (degrees)	FIG.
FIB1	60	2	0.90	2	140	Yes	/	/	/	FIG. 4a
FIB2	60	3	0.89	3	140	Yes	140	/	/	FIG. 4b
FIB3	60	3	0.89	4	140	Yes	140	Yes	/	FIG. 4c
FIB4	60	3	0.89	5	140	Yes	140	Yes	140	FIG. 4d
FIB5	54	1	1.00	/	/	/	/	/	/	FIG. 4e

$\alpha$  Included angle between the main axis of the middle portion and the main axis of the 1<sup>st</sup> straight section

$\beta$  Included angle between the main axis of the 2<sup>nd</sup> straight section and the main axis of the 3<sup>rd</sup> straight section

$\gamma$  Included angle between the main axis of the 4<sup>th</sup> straight section and the main axis of the 5<sup>th</sup> straight section

TABLE 3

Fibre type	Dosage (kg/m <sup>3</sup> )	$f_L$	$f_{R,1}$	$f_{R,2}$	$f_{R,3}$	$f_{R,3}/f_{R,1}$
FIB1	40	5.48	3.75	3.85	3.68	0.98
FIB5	40	5.80	4.11	4.31	2.83	0.69

TABLE 4

Fibre type	Dosage (kg/m <sup>3</sup> )	$f_L$	$f_{R,1}$	$f_{R,2}$	$f_{R,3}$	$f_{R,3}/f_{R,1}$
FIB2	40	5.81	5.02	6.01	5.89	1.17
FIB3	40	5.79	5.76	7.40	7.46	1.30
FIB3	20	5.56	3.06	3.51	3.54	1.16
FIB4	40	5.89	5.23	6.65	6.75	1.29

From Table 3 and Table 4 it can be concluded that the ratio  $f_{R,3}/f_{R,1}$  of the prior art fibres (FIB1 and FIB5) is below 1 whereas the ratio  $f_{R,3}/f_{R,1}$  of the steel fibres according to the present invention (FIB2, FIB3 and FIB4) is higher than 1.

The residual flexural tensile strengths  $f_{R,1}$ ,  $f_{R,2}$  and  $f_{R,3}$  of the prior art fibres (FIB1 and FIB5) are low, i.e. considerably lower than the residual flexural tensile strengths  $f_{R,1}$ ,  $f_{R,2}$  and  $f_{R,3}$  of the fibres according to the invention (FIB2, FIB3 and FIB4).

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Comparing the steel fibres according to the present invention (FIB2, FIB3 and FIB4) using a dosage of 40 kg/m<sup>3</sup> with the prior art steel fibres (FIB1 and FIB5) using a dosage of 40 kg/m<sup>3</sup>, the residual flexural tensile strengths  $f_{R,1}$ ,  $f_{R,2}$  and  $f_{R,3}$  of the steel fibres according to the present invention are considerably higher than for the prior art fibres.

Steel fibre FIB3 is tested in two different dosages: 20 kg/m<sup>3</sup> and 40 kg/m<sup>3</sup>. Even when a fibre dosage of 20 kg/m<sup>3</sup> is used the ratio  $f_{R,3}/f_{R,1}$  is exceeding 1. This indicates that such steel fibres behave like traditional reinforcing steel (stress-strain based instead of stress-crack opening based).

Comparing steel fibres FIB2, FIB3 and FIB4 it can be concluded that the residual flexural tensile strengths  $f_{R,1}$ ,  $f_{R,2}$  and  $f_{R,3}$  are increasing by increasing the number of straight sections from 3 to 4.

Also the ratio  $f_{R,3}/f_{R,1}$  is increasing by increasing the number of straight sections from 3 to 4.

By increasing the number of straight sections from 4 to 5, the residual flexural tensile strengths  $f_{R,1}$ ,  $f_{R,2}$  and  $f_{R,3}$  and the ratio  $f_{R,3}/f_{R,1}$  is no further increased.

Surprisingly, steel fibres with anchorage ends having four straight sections shows the best performance.

When the steel fibres of Table 2 are subjected to a pull out test to determine the anchorage force, steel fibre FIB3 (having four straight sections) has the best anchorage in concrete.

As a matter of example, steel fibres according to the invention may be made as follows.

Starting material is a wire rod with a diameter of e.g. 5.5 mm or 6.5 mm and a steel composition having a minimum carbon content of for example 0.50 per cent by weight (wt %), e.g. equal to or more than 0.60 wt %, a manganese content ranging from 0.20 wt % to 0.80 wt %, a silicon content ranging from 0.10 wt % to 0.40 wt %. The sulphur content is maximum 0.04 wt % and the phosphorous content is maximum 0.04 wt %. A typical steel composition comprises 0.725% carbon, 0.550% manganese, 0.250% silicon, 0.015% sulphur and 0.015% phosphorus.

An alternative steel composition comprises 0.825% carbon, 0.520% manganese, 0.230% silicon, 0.008% sulphur and 0.010% phosphorus. The wire rod is cold drawn in a number of drawing steps until its final diameter ranging from 0.20 mm to 1.20 mm.

In order to give the steel fibre its high elongation at fracture and at maximum load, the thus drawn wire may be subjected to a stress-relieving treatment, e.g. by passing the wire through a high-frequency or mid-frequency induction coil of a length that is adapted to the speed of the passing wire. It has been observed that a thermal treatment at a



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temperature of about 300° C. for a certain period of time results in a reduction of the tensile strength of about 10% without increasing the elongation at fracture and the elongation at maximum load. By slightly increasing the temperature, however, to more than 400° C., a further decrease of the tensile strength is observed and at the same time an increase in the elongation at fracture and an increase in the elongation at maximum load.

The wires may or may not be coated with a corrosion resistant coating such as a zinc or a zinc alloy coating, more particularly a zinc aluminium coating or a zinc aluminium magnesium coating. Prior to drawing or during drawing the wires may also be coated with a copper or copper alloy coating in order to facilitate the drawing operation.

The stress-relieved wires are then cut to the appropriate lengths of the steel fibres and the ends of the steel fibres are given the appropriate anchorage or thickening. Cutting and hook-shaping can also be done in one and the same operation step by means of appropriate rolls.

The thus obtained steel fibres may or may not be glued together according to U.S. Pat. No. 4,284,667.

In addition or alternatively, the obtained steel fibres may be put in a package, as for example a chain package or a belt like package. A chain package is for example disclosed in EP-B1-1383634; a belt like package is disclosed in European patent application with application number 09150267.4 of Applicant.

The invention claimed is:

1. A steel fibre configured to reinforce concrete or mortar, said steel fibre comprising:

a middle portion and anchorage ends at both ends of said middle portion,

said middle portion having a main axis,

each of said anchorage ends comprising at least a first straight section, a second straight section and a third straight section, said first straight section being connected to said middle portion by a first bent section, said second straight section being connected to said first straight section by a second bent section, said third straight section being connected to said second straight section by a third bent section,

each of said first, second and third straight sections having a main axis, wherein said first straight section is configured to bend away from the main axis of said middle portion thereby defining an included angle between the main axis of said middle portion and the main axis of said first straight section, said second straight section being substantially parallel with the main axis of said middle portion, and said third straight section is configured to bend away from the main axis of said middle portion in the same direction as said first straight section is configured to bend away from the main axis of said middle portion thereby defining an included angle between the main axis of said second straight section and the main axis of said third straight section, said included angle between the main axis of said middle portion and the main axis of said first straight section and said included angle between the main axis of said second straight section and the main axis of said third straight section ranges between 100 and 160 degrees,

wherein said middle portion has a length greater than 25 mm and said first straight section, said second straight

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section, and said third straight section each has a length between 0.1 mm and 8 mm.

2. The steel fibre according to claim 1, wherein said anchorage end further comprises a fourth straight section, said fourth straight section being connected to said third straight section by a fourth bent section.

3. The steel fibre according to claim 2, wherein said fourth straight section has a main axis that is substantially parallel with said main axis of said middle portion.

4. The steel fibre according to claim 2, wherein the angle between the main axis of the fourth straight section and said main axis of said middle portion ranges between -60 and +60 degrees.

5. The steel fibre according to claim 1, wherein the included angle between the main axis of said middle portion and the main axis of said first straight section and the included angle between the main axis of said second straight section and the main axis of said third straight section are the same.

6. The steel fibre according to claim 1, wherein said middle portion of said steel fibre has a tensile strength  $R_m$  of at least 1000 MPa.

7. The steel fibre according to claim 1, wherein said middle portion has an elongation at maximum load  $A_{g+e}$  of at least 2.5%.

8. The steel fibre according to claim 1, wherein said steel fibre is in a stress-relieved state.

9. The steel fibre according to claim 1, wherein said middle portion of said steel fibre is provided with at least one flattened section.

10. The steel fibre according to claim 1, wherein said middle portion of said steel fibre has a diameter D ranging from 0.1 mm to 1.20 mm.

11. The steel fibre according to claim 1, wherein said steel fibre has a length to diameter ratio L/D ranging from 40 to 100.

12. A concrete structure reinforced with steel fibres according to claim 1.

13. The concrete structure according to claim 12, wherein the ratio residual flexural tensile strength  $f_{R,3}$  divided by residual flexural tensile strength  $f_{R,1}$  ( $f_{R,3}/f_{R,1}$ ) is higher than 1 with a dosage of said steel fibres of less than 1 vol %.

14. The concrete structure according to claim 12, wherein the residual flexural tensile strength  $f_{R,3}$  is higher than 5 MPa with a dosage of said steel fibres of less than 1 vol %.

15. A method using the steel fibre according to claim 1 for a load carrying structure of concrete by placing the steel fibre in the load-carrying structure.

16. The steel fibre according to claim 1, wherein said included angle between the main axis of said middle portion and the main axis of said first straight section and said included angle between the main axis of said second straight section and the main axis of said third straight section are different.

17. The steel fibre according to claim 1, wherein the anchorage ends bend in opposite directions from the main axis of the middle portion.

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